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Bayesian Network applications for environmental risk assessment

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ACADEMIC DISSERTATION

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II. Lehikoinen, A., Luoma, E., Mäntyniemi, S. and Kuikka, S. 2013. Optimizing the Recovery Efficiency of Finnish Oil Combating Vessels in the Gulf of Finland Using Bayesian Networks. *Environmental Science and Technology*, 47(4):1792-1799.

III. Lehikoinen, A., Hänninen, M., Storgård, J., Luoma, E., Mäntyniemi, S. and Kuikka, S. 2014. A causal model for assessing the collision induced risk of an oil accident in the Gulf of Finland. *Submitted to Environmental Science and Technology.*

IV. Jolma, A., Lehikoinen, A., Helle, I. and Venesjärvi, R. 2014. A software system for assessing the spatially distributed ecological risk posed by oil shipping. *Environmental Modelling and Software,* 61: 1-11.

V. Uusitalo, L., Lehikoinen, A., Helle, I. and Myrberg, K. 2014. Onto the uncertainty: utilizing deterministic models in probabilistic decision support in environmental management. *Submitted to Environmental Modelling and Software*.

Individual contributions of the authors of articles

I. A. Lehikoinen had the main responsibility in planning and constructing the metamodel, handling the simulation data received from the Finnish Environment Institute (SYKE), conducting the analysis and in writing the article. The data for Fucus vesiculosus submodel was gathered from the database of Finnish Environment Institute by A. Lehikoinen and E. Klemola. I. Helle conducted test runs with the metamodel and participated in constructing the final version. S. Mäntyniemi provided support in different types of methodological questions. S. Kuikka provided several ideas and comments that directed the work. H. Pitkänen from Finnish Environment Institute provided the simulation runs for the nutrient loads and ecological status indicators. All the authors participated in writing the article.

II. A. Lehikoinen had the main responsibility in phrasing the analytical question and in planning the model structure and functional principle. She supervised the master's thesis work of E. Luoma, who carried out the expert interviews and constructed the first version of the model. A. Lehikoinen revised and fine-tuned the model for publication, conducted the analysis and was the corresponding author of the article. S. Mäntyniemi and S. Kuikka provided methodological support and comments. All the authors participated in writing the article.

III. A. Lehikoinen had the main responsibility in planning and constructing the metamodel and in collecting and compiling the data used. She conducted the analysis and was the corresponding author of the manuscript. M. Hänninen and J. Storgård participated in defining causalities in different parts of the metamodel and provided data and information related to their own areas of expertise. E. Luoma conducted runs with the existing models to produce priors for the metamodel. S. Mäntyniemi and S. Kuikka provided methodological support and comments through the process. The original idea of the work came from S. Kuikka. All the authors participated in writing the manuscript.

IV. The first idea of the spatial risk assessment software and its functional principle was A. Lehikoinen's own. A. Jolma was responsible for the practical development of the method, as well as the data handling and coding work. A. Lehikoinen provided the Bayesian Network serving as one element of the software. In co-operation with I. Helle, A. Lehikoinen designed the software functionalities and defined the required features of the oil drift simulation runs, which were ordered from Finnish Environment Institute. The valuation part of the software was designed by Lehikoinen, Helle and Venesjärvi. A. Jolma was the responsible author of the manuscript, but A. Lehikoinen had reasonable role in the writing process. All the authors participated in writing the manuscript.

V. A. Lehikoinen had a reasonable role in planning and writing the article. L. Uusitalo was the responsible author. I. Helle participated in writing and reworking the paper. K. Myrberg provided his perspective to the topic and commented the text.

Abstract

Environmental risk assessment (ERA) is a process of estimating the probability and consequences of an adverse event due to pressures or changes in environmental conditions resulting from human activities. Its purpose is to search the optimal courses of action under uncertainty when striving for the sustainable use of environment through minimizing the potential losses. As environmental issues are typically multidisciplinary, addressing large amount of eco-societal inter-linkages, an optimal tool for the ERA should enable the efficient integration and meta-analysis of multidisciplinary knowledge. By describing the causalities and studying the interactions among its components, this kind of integrative analysis provides us better understanding about the environmental system in focus. In addition, the functional ERA application should allow exploring, explaining and forecasting the responses of an environmental system to changes in natural and human induced stressors, serving as a decision support model that enables the search of optimal management strategy, also in the presence of imperfect knowledge.

Bayesian Network (BN) is a graphical model that enables the integration of both quantitative and qualitative data and knowledge to a causal chain of inference. It is a powerful tool for synthesising knowledge, logic and rules, providing aid for thinking about complex systems that are too demanding to be analysed by human brains alone. In a BN, all the knowledge is handled in the form of probability distributions, thus the result represents the prevailing state of knowledge. The method facilitates analysing the location and amount of uncertainty explicitly, as well as enables studying its significance when it comes to the decision making.

The main contribution of this thesis is to share experiences and ideas about the development and use of the ERA applications executed by using the BN as method. The perspective of the work is dichotomic. The objective in the separate studies presented in the articles have been on one hand to develop tools for integrating available knowledge and materials to enable the quantitative assessment of the environmental risks. On the other hand, the ultimate aim has been to learn more about the environmental risks and their potential management in the case study area of the Gulf of Finland. In this thesis, both of these perspectives are considered. Eutrophication and oil transportations at the Gulf of Finland are used as the case issues.

The thesis concludes that Bayesian networks have plenty of properties that are useful for ERA and the method can be used for solving problems typical for that field analytically. By planting the developed graphical BNs in the commonly used *Drivers-Pressures-States-Impacts-Responses* - problem structuring framework, it is also demonstrated that combining these two approaches can be helpful in conceptual modeling, enabling the better framing of the research problem at hand and thinking about it systematically. The greatest challenges concerning the BN-ERA modeling are found to be related to the computational limitations of the current BN software, when it comes to the joint use of the discretised and continuous variables, as well as the restricted capacity to include the spatial resolution to the models. Producing the prior probability distributions by using deterministic models is also noted to be relatively tedious and time-consuming. The issues of end use of the applications, problems related to the scientific publishing of them, as well as the advantages and challenges of working in the multidisciplinary research teams are discussed.

1. Introduction

Life is about making trade-offs. In general, all the human activities have potential to cause harm to our own living environment (Calow, 1998; Dietz, 2003). Usually there are alternative courses of action to supply the human needs with less negative environmental effects, but it requires concessions in some other sectors of life. Risk assessment is about searching of balance among competing interests and concerns (Jardine et al., 2003). Environmental issues are typically multidisciplinary by nature, dealing with natural interactions as well as societal and economic issues and thus being linked to several interests and aims (Lubhenco, 1998). In addition, the valuation of the environment and natural resources is subjective and context dependent a question; thus, finding a balance is usually a very challenging task (Burgman, 2005).

The title of my thesis is quite "risky" as such, as it includes two terms having a wide variety of definitions in the literature, namely *environment* and *risk*. This work takes a perspective where *environmental* refers to the living environment of both humans and wildlife (after Calow, 1998), environmental risk thus being the risk to species (including people), natural communities and ecosystem processes (Burgman, 2005). *Risk* as a number is handled as a combination of a potential adverse event, its consequences and the uncertainty related to both (e.g. Aven, 2010). It is still acknowledged that risk is a highly subjective concept involving several psychology-related aspects, such as the variability in individuals' objectives and values (Slovic et al., 2004; Burgman, 2005). Also the degrees of belief concerning the structure and functioning of the studied systems, as well as the views on the amount of uncertainty related to them vary among the people (Siu and Yang, 1999; O'Hagan et al., 2006).

The process of environmental risk management (Figure 1) is often seen as an adaptive cycle that covers the elements of risk assessment, risk management (regulation), monitoring and validation, as well as risk communication and updating (e.g. Burgman, 2005; Jardine et al., 2003). The terminology and grouping of the elements varies to some extent with the approach. As understood in this thesis, *risk assessment* covers problem formulation, identification of risks and management options as well as the estimation of uncertainty (after Burgman, 2005). In other words, environmental risk assessment (ERA) is a process of estimating the probability and consequences of an adverse event due to pressures or changes in environmental conditions resulting from human activities. Its main purpose is to provide help in the search of optimal decisions under uncertainty.

The environment is a universal system that covers endless amount of interlinkages among the living organisms and their physical surroundings. Even for carefully defined fixed subsystems, understanding the causalities between the elements and how the system performance could be optimized is a challenging task that requires a large consortium of experts from different scientific disciplines (EPA, 2008). Integrated assessment modelling, i.e. integration of the data, expert knowledge and results of the domain models offered by the consortium to one systemic metamodel, provides us better conceptual understanding about the environmental system in focus (Jakeman and Letcher, 2003; Laniak et al., 2013; Whelan et al., 2014). The purpose of the approach is to describe the causalities in the system by studying the interactions and cross-linkages among its components, providing information that is useful in the environmental management context.

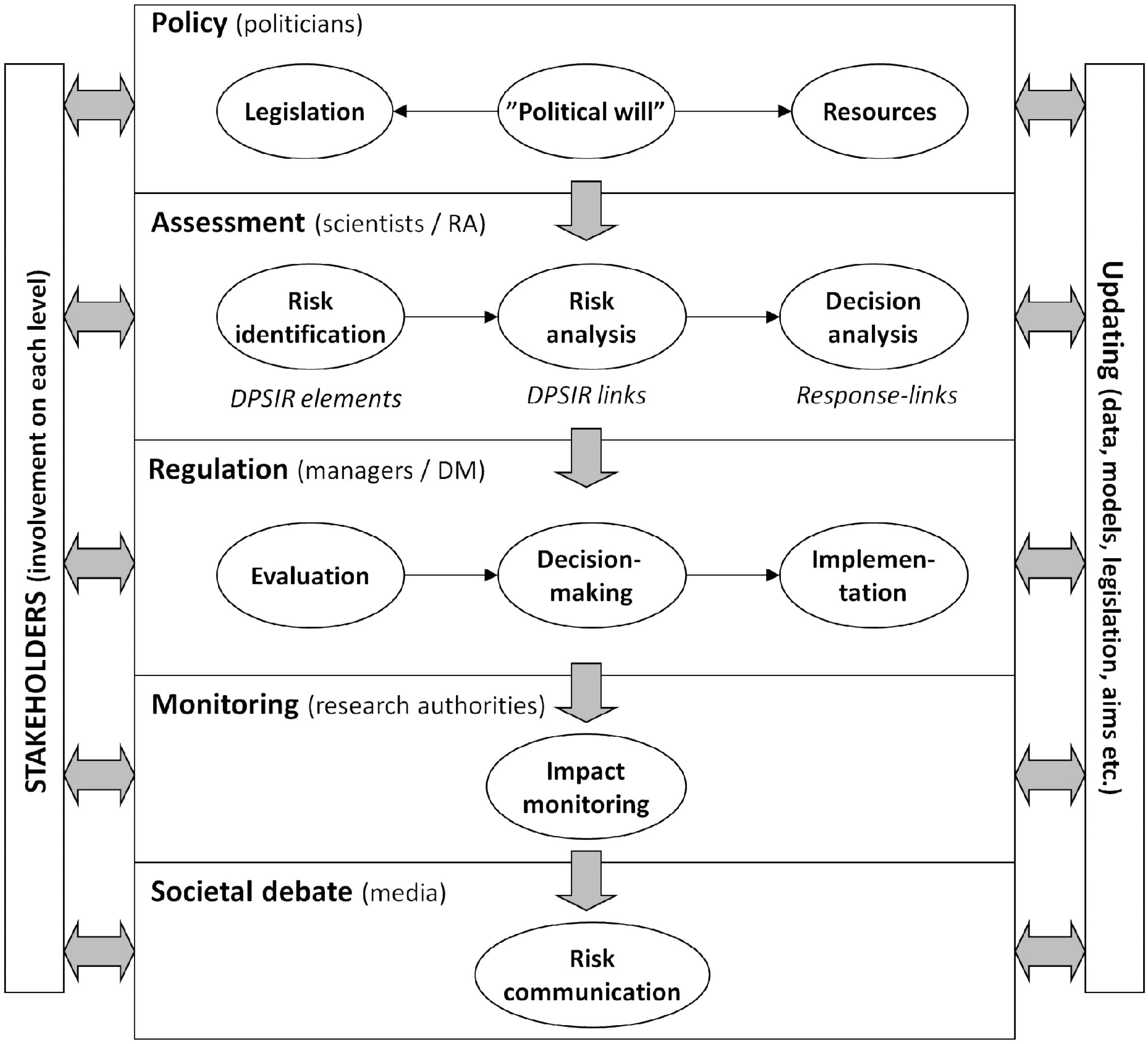

Figure 1. The process of environmental risk management, flow chart showing the key players and focal terminology as they are understood in this thesis. RA means *risk assessor*, DM is *decision maker*. DPSIR refers to the Drivers - Pressures - States - Impacts - Responses -framework, explained and applied in chapter 5. Grey arrows depict flow of information. Optimally, communication should happen among all the organisational levels, also from bottom-up, thus the figure is a simplification.

An optimal tool for the integrated assessment of environmental risks forms a science-based platform for structuring and organising multi-disciplinary knowledge (Whelan et al., 2014). It can be used for exploring, explaining and forecasting the responses of an environmental system to changes in natural and human induced stressors. Thus, it also serves as a decision support model, allowing the search of optimal management strategy in the presence of imperfect knowledge (McIntosh et al., 2011). An optimal integrated ERA tool allows the inclusion of both qualitative and quantitative data and knowledge into the same analysis and enables quantifying the subjective aspects of risks. In addition, the tool should be transparent and visual when it comes to the problem framing and formulation, allowing the inclusion and illustration of uncertainty at each step of the analysis. By evaluating the nature and extent of the uncertainties, the assessment provides a realistic picture of the possible outcomes of management actions (Power and McCarty, 2006; Ascough II et al., 2008; Fenton and Neil, 2012). In most cases, the analysis should cover spatial and temporal variability too, thus an optimal tool should answer this call.

While conducting the case studies that form part of this thesis, I have experienced that Bayesian networks (BN) are a potential method for covering several characteristics of the optimal integrated modelling tool for ERA. They provide a manageable platform for compiling and structuring knowledge of different types and forms (e.g. Reichert et al., 2007). Because of their graphic nature, BNs are transparent and enable the visual representation of both the problem formulation and the results – including the uncertainty related to each element of the system (Fenton and Neil, 2012). This makes BNs applicable also to supporting discussions both within the interdisciplinary modelling teams and with the external stakeholders (e.g. Reichert et al., 2007; Holzkämper et al., 2012). For constructing the large integrated models, BNs are superior, having a modular nature that enables building large entities piece by piece by adding new variables or connecting whole BN models with each other to form a larger entity (e.g. Molina et al., 2010; Borsuk et al., 2012). This allows long-term development of holistic ERA systems which cannot be developed during a single project. These and some other positive properties, as well as the negative ones, are discussed further in the other parts of the summary, where also the closer description of the method and more thorough literature review are left.

Integrated assessment requires people from different disciplines and backgrounds, representing divergent research cultures and traditions, to come together and commit to sharing and implementing their ideas (EPA, 2008; Holzkämper et al., 2012). Translating the knowledge base, views and results of the non-modelers to the language of numerical analyses claims for advanced mutual understanding gained through the development of a common language. What comes to the integrated modelling, two types of modelers are needed - specialists in individual domain models and the experts representing the systemic view and managing the model integration. Well developed trust, understanding, transparency and collaboration among the research group are required to successfully integrate disciplines within a model (Catney and Lerner, 2009; Haapasaari et al., 2012). Thus, integrated assessment modelling is much more than just a modelling exercise. It is also about being e.g. a project coordinator, facilitator, student and a diplomat – the aspect discussed also by Kragt et al. (2013).

Box 1. Terms related to ERA as they are denoted in this summary

Risk: a combination of a potential adverse event, its consequences and the uncertainty related to both. (Aven, 2010)

Environmental risk: risk to species (incl. people), natural communities and ecosystem processes. (Burgman, 2005)

Risk assessment: evaluates the magnitude of the risk within a decision making context (Jakeman, 2003; Laniak, 2013) and provides information in the search of optimal decisions under uncertainty. (Burgman, 2005)

Modelling: an analytic approach that aims for constructing a simplified representation of reality to understand it and potentially predict and control its future development. (Hilborn & Mangel, 1997)

Integrated environmental modelling: a system's analytic approach to environmental assessment, bringing together knowledge and elements from a variety of disciplinary sources (models, data, and assessment methods). (EPA, 2008; Laniak et al., 2013)

Integrated environmental risk assessment modelling: a system's analytic approach for holistic understanding and evaluation of the environmental risks to provide support for management planning. Allows comparison between risk control options and scenarios by simulating their consequences. (derived from the previous)

Box 2. Terms related to integrated modelling and systems analysis (as defined in Barton, 2007)

Synthesis: a procedure by which separate elements or components are combined in order to form a coherent whole.

Analysis: a procedure to break down an intellectual or substantial whole into parts or components. Provides explanations of how things work.

System: a cognitive construct for making sense of complexity and the organization of knowledge.

System's thinking: provides a distinctive approach to the manner in which both analysis and synthesis operate within the scientific process.

The objective of this summary is to share my experiences and ideas on developing integrated models for environmental risk assessment (ERA), using the Bayesian Networks (BN) as a method. The perspective of this work is dichotomic. Having my background in substance areas of limnology and environmental science, I see my viewpoints to represent not only the system modeler's but also the end-user's stand. The objective in my studies have been on one hand to develop tools that allow the synthesis of available knowledge and materials to enable the quantitative assessment of environmental risks. On the other hand, the main aim behind this all has been to find answers and to learn about the environmental risks and their potential management in the case study area of the Gulf of Finland. In this summary, both of these perspectives are considered. My thoughts concerning BNs as a method for ERA, as well as the applications that have been developed by using them, will form the thread of the text. In addition I will touch on the system's analytic insights gained concerning the two different types of environmental risks that are used as the case problems in the articles, namely eutrophication and oil accidents.

2. Bayesian Networks as tools for integrated ERA

Bayesian networks (BN) are relatively well recognised to be an advantageous method for different types of environmental models. The published literature includes studies covering a wide variety of perspetives, e.g. decision analytic issues (Kuikka et al., 1999; Helle et al., 2010; Barton et al., 2008), integrated modelling (Varis and Kuikka, 1997; Borsuk et al., 2012; Rahikainen et al., 2014; Molina et al., 2010) and participatory modelling (Bromley et al., 2005; Castelletti and Soncini-Sessa, 2007; Carmona et al., 2011; Mäntyniemi et al., 2013). Many of the above mentioned works would actually fit to more than one of the classes. The BNs have been used also for analysing human induced uncertainty in the implementation on the management actions (Haapasaari et al., 2007; Haapasaari and Karjalainen, 2010) and for compiling and formalizing expert knowledge (Lecklin et al., 2011). Reviews considering the topic of using BNs in the environmental modelling are published by Uusitalo (2007), Aquilera et al. (2011) and Barton et al. (2012).

Based on literature search using an academic bibliographic database (Scopus, April 2014), BNs have been most frequently used for risk assessment in the field of engineering studies (key words "Bayesian network" and "risk assessment" resulted in 571 scientific papers), reviewed by Weber et al. (2012). Computer sciences are in the second place (269 papers) whereas medicine (170 papers), mathematics (159 papers) and environmental sciences (156 papers) are rather even. The first environmental risk assessments applying BNs were published at the end of the 20th century by Varis and Kettunen (1988), Freeze et al. (1992) and Varis and Kuikka (1997). Since then the method has gained popularity among environmentalists and in the year 2013, 21 environmental risk assessment articles were listed. Their topics cover wide variety of issues from oil spill cleanup costs (Montewka et al., 2013) and ecosystem services-based resource management (Grêt-Regamey et al., 2013) to ecological quality assessment of estuarines (Tableau et al., 2013). All in all 235 environmental articles having BN as a keyword were listed for the year 2013.

2.1. Principle of the method

BNs are graphical models for causal reasoning under uncertainty (Jensen and Nielsen, 2007). The inference within a BN follows a mathematical rule, originally discovered by an English Reverend Thomas Bayes (Bayes and Price, 1736). The Bayesian logic has been compared to the apparent functioning and the learning principle of human brains (McGrayne, 2011). To put it simple: every observation that we make is used to update our former (prior) belief, which results in new, improved (posterior) understanding. The rule is then used iteratively, i.e. every new observation further updates our former posterior, which is in this case used as a new prior. The Bayesian logic is also called "inverse logic" because it can be used not only for predicting events given the causing factors but also for inferring the likely causes based on the observed events (Fienberg, 2006; McGrayne, 2011). This enables efficient systemic learning and makes Bayesian models powerful tools also for environmental analyses.

A BN has two representations: the graphical and the numerical one. The graphical representation is an acyclic graph, describing relationships (denoted by directed arcs) between variables (nodes). The relations are defined in the numerical representation by populating the node-specific conditional probability tables (CPT) with conditional probability distributions (CPD). A CPD contains information on the probability of a variable being in a certain state depending on the state of its explanatory parent variables. For defining the numerical dependencies, a wide variety of methods can be applied, beginning from the simulations of either deterministic (Dorner et al., 2007) or probabilistic approach (Rahikainen et al., 2014), or the direct use of "hard data" by utilizing different learning algorithms (Riggelsen, 2006; Uusitalo et al., 2011). Under the belief that future events are exchangeable with the series of earlier observations, the statistical frequency distributions can be utilized as well (Juntunen et al., 2005). In data- or resource-poor cases, eliciting the degrees of belief of the persons who are thought to be experts of the analyzed issue, are widely used (e.g. Kuikka and Varis, 1997; Uusitalo et al., 2005; O'Hagan et al., 2006, Mäntyniemi et al., 2013). In the context of ERA this is often a meaningful alternative as the analysis typically considers rare events or the level of undesired development potential to occur in the future, but not yet materialized. Sometimes the need for assessment may be critical, but the resources for the allocation of time and money are restricted. In those cases a systematic representation of the expert knowledge is a particularly valuable tool.

In a BN, each of the explanatory variables (parents) explains part of the uncertainty in its child variable. A BN enables studying the probability distribution of each variable under the prevailing state of knowledge (Figure 2), which can be defined by locking certain variables in an actually or hypothetically observed state. This action updates the probability distributions of the other variables accordingly. In Figure 2, the inverse reasoning is demonstrated as the model infers the states of the indicators when the ecosystem's status is locked.

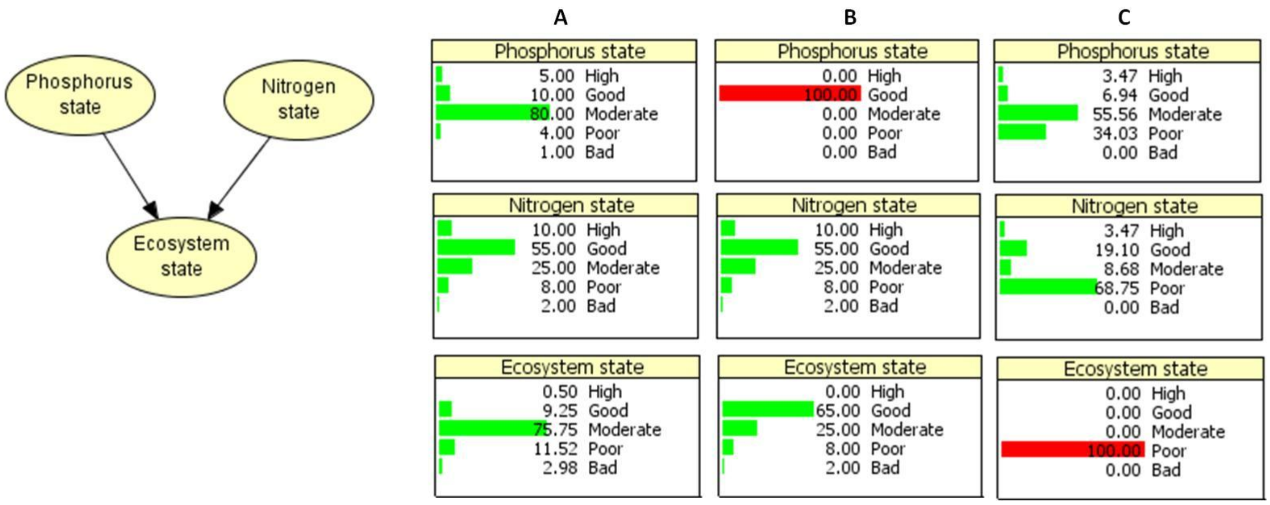

Figure 2. An example of a discrete BN and its principle. The state of the ecosystem is conditional to the state of indicator variables nitrogen and phosphorus, each variable having five alternative status classes. In this example the indicator being in the worst state is thought to define the status of the whole ecosystem. In case A, none of the variables are locked ("observed"), whereas in cases B and C red bars show the locked states. The numbers summing up to 100% (thus indicating that the whole range of possibilities is covered) are showing the probabilities of each class to occur.

Figure 2 gives an example of a BN consisting of three chance (or random) nodes, i.e. stochastic variables. A BN augmented with decision nodes (usually illustrated by rectangles) and utility nodes (illustrated by diamonds) is called an *influence diagram* (ID) (Howard and Matheson, 2005). ID is a generalization of a BN, capable of solving decision making problems (Jensen and Nielsen, 2007). One decision node covers those decisions that are alternative to each other. If some of the decisions could be implemented in parallel, those are given the nodes of their own (see Figure 3). The utility nodes should link to the variables related to our objectives. The criteria, against which the decisions are evaluated, are defined in utility nodes expressing relative preferences for all the alternative outputs of the target variables. An ID can then compute the expected utilities of all combinations of decision options given the state of knowledge in the network.

The network can also have a hierarchical structure, i.e. another network inserted within the main model as a submodel (Figure 3). These applications are called Object-Oriented Bayesian Networks (OOBN, Koller and Pfeffer, 1997). The OOBN can be viewed as a hierarchical description of a larger problem domain (Weidl et al., 2005). OOBNs can be utilized for "time-slicing", to be able to create dynamic and adaptive time-step BNs despite the requirement for the acyclic structure (e.g. Weber, 2006; Carmona et al., 2011; Johnson and Mengersen 2012). This is important to note if the system's evolution is in focus, because as Figure 1 pointed out, the environmental management framework is a self-updating, adaptive system. Another way to make use of the OOBNs is to create "organizational" applications by decomposing the highly complex global model to master- and sub-networks (Borsuk et al., 2004; Barton et al., 2008; Molina et al., 2010). This is how the OOBNs are applied in papers I-III. The main advantage in here is that by representing a complex system consisting of multiple interlinked sub-systems as an OOBN, the knowledge can be decentralised and structured into better manageable and conceivable elements (Weber, 2006). In paper I of this thesis, own submodel for each of the analysed coastal areas is addressed. In paper II, vessel-specific submodels are used to gather the individual attributes of the ten oil combating ships and their mutual dynamics in a manageable manner. In paper III, the stepwise risk assessment chain is executed by separating each of the additional elements (one of them being a condensed version of the entity presented in paper II) into a submodel of its own.

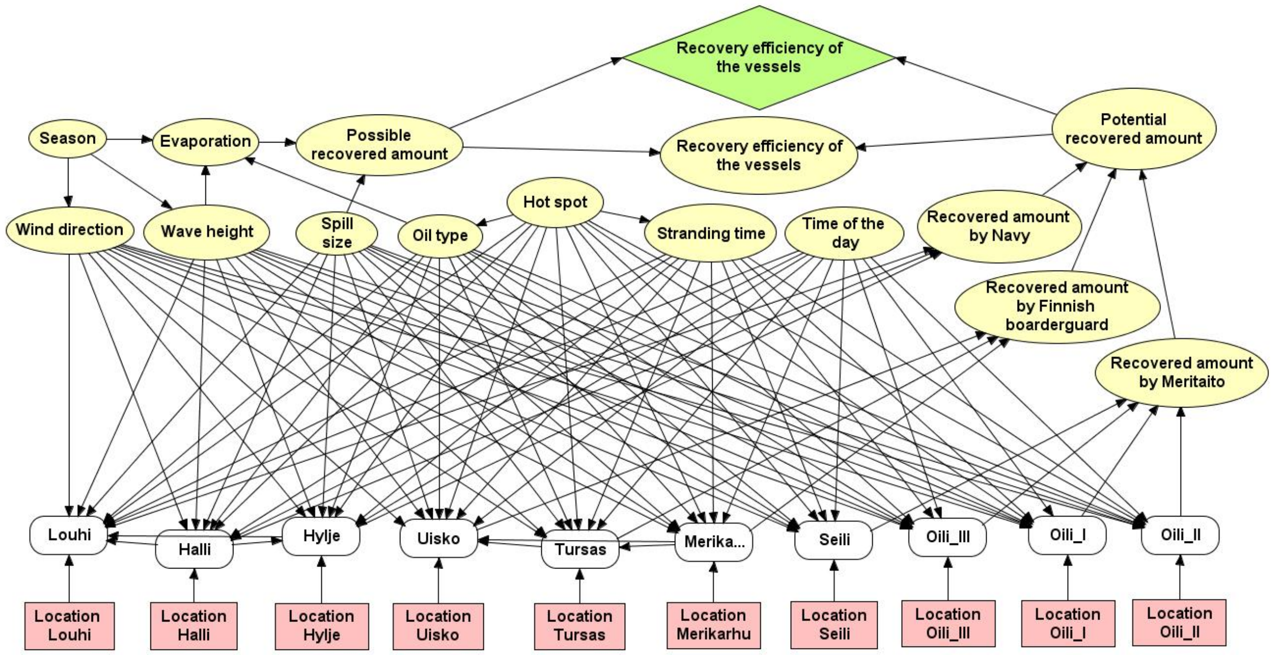

Figure 3. A complex ID, where ten decisions (choosing the best home harbors for the oil combating vessels) have to be made in parallel. Maximal oil recovery capacity, given the uncertain weather conditions and oil spill parameters, is the criteria used for the decision ranking. The vessel-specific models are integrated into the ID as submodels (the white rounded rectangles), thus the diagram also represents an OOBN. The figure is taken from paper II.

2.2. Advantages from the ERA perspective

A BN or ID can be regarded as a kind of scenario synthesis where all possible combinations of events are taken into account by weighting them according to how likely they are. Compared with the traditional risk assessments that are typically based on fixed point scenarios, the IDs provide more flexibility. A scenario can be handled as partly or fully unknown, which allows the search for the best action even when we don't know which of the included outlooks will materialize. As the performance of even rather complex discrete IDs is relatively fast with the latest computers, large packages of "what-if" questions can be tested and compared within a reasonable time.

Objective in the causal risk modelling is, by exploring the causalities in the system, to get insights on how to best control it. When presented with the illustration of its graphic structure, the logic of a causal model is clear. The transparent depiction of the system leads to minimal ambiguity which helps to understand how risks emerge and are interlinked (Fenton and Neil, 2012). According to Fenton and Neil (2012), risk is best characterized by a causal chain specifying and illustrating the triggers and controlling factors of the system, as well as consequences and mitigants for them. Compared with the traditional input – output ("black box") models, where the logic of inference is not available for inspection, a BN provides more reasonable description of the risk as all those elements and their interrelations are described. Further on, the risk is perspective dependent. What should be considered as an event and what as the consequence is a subjective question. An advantage in using BN for the risk assessment is that different risk perspectives can be analysed within a single model and the current probabilities associated with each of the elements can be studied at any stage.

The purpose of the decision analysis is not only to find the action that produces the greatest expected utility, but also to help the decision maker to better understand the system and its functioning (Keeney, 1982; Varis and Kuikka, 1997; Kiker et al., 2005). BNs are powerful tools for system's analysis. They enable integration of and interplay between the materials and methods that are otherwise thought to be beyond each other (Varis and Kuikka, 1997). The method also allows an effective synthesis of the work done in separate BN projects as any two networks having at least one identical node can be interlinked to form a more holistic system. The integration starts a two-way information flow between the sub-systems, which may provide interesting insights on how they are interrelated. My personal experience is that the value of information (VOI) analysis can provide valuable system's analytic insights. It can be used to sort out a value of knowing better the state of a variable, if the utility in the model is defined in monetary terms (Mäntyniemi et al., 2009). In the applications of papers II and III, applying only nonmonetary valuation, the VOI analysis helped in defining those variables that have the greatest impact on the analysed decisions, i.e. kind of systemic "key factors". This information can also be utilized to allocate the forthcoming research towards the most relevant issues (e.g. Fischhoff, 2000; Morgan, 2005).

The visuality of the BNs is a remarkable feature in the ERA context. First of all, as cause and effect are the basic elements of scientific thinking, even those scientists without thorough understanding about the probabilistic reasoning are capable of constructing reasonable models and conduct relevant analyses by using the method (Borsuk et al., 2012). Also when eliciting the relevant variables and their interlinkages from the stakeholders, the causal presentation is a natural way to illustrate their ideas. Because of the easy-to-understand presentation of both the problem structuring and the quantitative results (presented as visual distributions), BNs are also utilised in supporting the consensus building among the contradictory stakeholder parties (Henriksen et al., 2007). When it comes to this thesis, external (outside the research team) stakeholder / expert knowledge was utilised especially in the applications of papers II and III. In all the case studies (papers I-IV), BNs have still had a remarkable role within the interdisciplinary research teams in supporting the problem framing as well as finding the consensus concerning the appropriate way of integration and distribution of work when creating the integrative models. These issues have not been central themes in these papers, but will be concerned in the forthcoming publications.

The risk attitude (Pratt 1964; Burgman, 2005) of a decision maker is a crucial factor when the best management action should be defined. It is closely related to peoples' risk perception, which includes the level of risk aversion (Pratt, 1964; Varis and Kuikka, 1997). It seems that the level and type of uncertainty can affect the risk attitude of a person (Chow and Sarin, 2002). According to the decision theory, the best action is the one that maximizes the total expected utility, while minimizing the (potential) losses (Fenton and Neil, 2012). This is true only in the ideal situation where the model truly represents the decision-maker's personal world-view, covering all the relevant variables, aspects of uncertainty as well as his/her values and risk attitude. In practice, that kind of models hardly exists, already because we are conscious of the fact that our knowledge –

even the probabilistic representation of it – is not perfect. For example, if the utility function does not correctly reflect the decision makers risk aversion, then the rank of alternative decisions may not be optimal. It might be that the management alternative producing the highest expected utility also has the greatest uncertainty concerning the output, including even possibility for a total failure. At the same time an alternative with smaller expected utility may affect through a relatively well known mechanisms, thus resulting in less uncertain end results with negligible probability for the failure. The latter alternative of this example would be appealing to a more risk-averse person who would give more weight to avoiding the total failure. For the decision analysis to recommend this option, the true preferences about the outcome should be encoded in the utility function. Also, when developing a decision model for the common use or research purposes, the valuation should not be based on anyone's personal views, but on some commonly agreed or at least clear and reasonable objectives. For the above mentioned reasons, being transparent with the uncertainty related to the results of the decision analysis is very important, making the IDs especially suitable tool for the risk assessment purposes as well (Borsuk, 2004).

2.3. Shortcomings and challenges

In all the applications of papers I - IV, Hugin Researcher software (Madsen et al., 2005) has been the tool used for the analysis. The constraint of this type of interactive BN software is that so far they are not capable of full joint modelling of the continuous and discrete variables (Borsuk et al., 2012). Thus, I have ended up to handle all the variables as discrete - even those clearly continuous by nature. The more classes we can assign to the variable, the more accurately its probability distribution can be estimated. As each additional class interval adds the computational complexity of the model, and increases the amount of CPDs to be defined in the child variables, the discretisation requires making trade-offs between the informativeness and accuracy of the model and the allocation of time and computational resources (e.g. Chen and Pollino, 2012). For example, when the oil amounts (in papers II-IV) or nutrient concentrations (paper I) are discretized, part of the changes in them, caused e.g. by the decisions, do not show in the results as they disappear within the two extremes of the defined interval. Recently the so called hybrid BNs, combining the continuous and discretized variables into the same model, have raised interest among the modelers because they enable building BNs with less vagueness and loss of information (Aguilera et al., 2010; Chen and Pollino, 2012).

One central problem of the BNs that I have faced when developing the applications, is the restricted capacity to include the spatial resolution to the models. In paper I the coastal area of southern Finland is divided into four, whereas in papers II-IV, five alternative zones and potential accident locations within them are included. As the amount of classes is restricted, building an application for the finer scale spatial analysis definitely claims for the integration of the BN to be run as a part of some spatial software. Solutions for integrating BNs and geographic information systems (GIS) have been presented in the literature, where either the GISs provide input for the BNs or vice versa (Smith et al., 2007 (a); Dlamini, 2010; Stelzenmüller et al., 2010; Johnson et al., 2012; McCloskey et al., 2011; Stelzenmüller et al., 2011). From my part, first steps towards this type of applications are described in paper IV, where a simple BN, huge amount of deterministic oil drift simulations and an observation database of threatened species are combined within spatial software. Probabilistic parameters for the oil drifting are modelled by the BN, after which drifting maps with uncertain parameters behind them are produced, defining for each map raster cell a probability to get oily. The amount of harm caused is analysed from the perspective of threatened species. The risk in a raster cell is then product of the probability to get oily and the sum of the conservation values of occurrences in that cell.

Paper V considers the problematics of using deterministic simulations and models to estimate the probabilistic causalities. Most of the applications that are developed to model different physical or ecological systems are not causal and probabilistic but deterministic input-output models, being confident about both the input and output values and thus providing only point estimates as their results. This is a common problem when developing integrative BNs (Dorner, 2007). Utilizing point estimates to populate CPTs of the metamodel typically claims for conducting a huge amount of runs with the deterministic model. I was faced with this problem when working with the applications presented in papers I (deterministic nutrient load and ecosystem models), III (deterministic model for geometrical collision probability) and IV (deterministic oil drifting model). Paper V explores alternative solutions for the problem.

3. Developing BN applications for ERA

In this chapter, focal issues concerning the process of developing an integrative ERA model by utilizing the BNs are highlighted. An important issue when planning the integrative BN-ERA model is to define the purpose and end users of the model (Chen and Pollino, 2012). The BN provides one possible structure to help in thinking the system and its management analytically. As all the models are subjective presentations of the real world (e.g. Hilborn and Mangel, 1997), the end user should agree with the model’s logic, to be able to accept the results it provides. Also the way in which the quantitative dependencies are defined, is important. If the end user doesn’t subscribe to the data and methods used, or thinks that the uncertainties are not acknowledged or presented extensively enough, his trust in the results is inevitably poor (e.g. Chow and Sarin, 2002). For this reason, the end user should be involved in the process of model building already from the planning phase (EPA, 2008; Laniak et al., 2013).

The applications presented in papers I-IV have been developed mainly the scientific research purposes in mind. Although the discussions with the external experts and stakeholders (a majority of them being potentially interested in the end results too) have naturally affected the problem framing and other solutions made, the applications have not been developed with any particular external end user in mind. The research consortioa have consisted of the scientific experts of the domain areas and the objective have been to strive for scientifically sound applications to the extent possible taking into account the subjective nature of the risk assessments. Thus, the primary end users have been the modelers themselves. The applications have been documented in detail in the form of final reports and scientific articles. Occasionally, the modelers have conducted analyses and presented the results by request.

When it comes to the integrative modeling issues, finding the consensus within the consortia have sometimes been challenging. Thus, developing the crossdisciplinary dialogue and thinking among the groups have been required. In this context it has also become evident that the linguistic uncertainty has a specific role in the multi-disciplinary teams, especially when the consortium is international and people are using strange terminology in a foreign language (see also Kragt et al., 2013). Skinner et al. (2014) criticise the common practice to separate the linguistic uncertainties into their own category (as e.g. in Burgman, 2005; Ascough II et al., 2008). They suggest the language uncertainties to rather be handled as epistemic not to forget that theoretically they can be quantified, reduced or even removed. This is a good point, as based on the literature search, there is lack of scientific studies and approaches to recognising and managing them.

An important issue closely related with the purpose of the model, is the correct amount of complexity (e.g. Hilborn and Mangel, 1997; Fenton and Neil, 2012; Skinner et al., 2014). According to the opinion presented by the Environmental Protection Agency of the USA (EPA, 2008), the level of complexity expressed in an integrative environmental decision modelling system should be determined as a function of the requirements for accuracy in results, the available data and models, as well as the available resources. In the scientific research projects, if no external end user have been specified, the two latter are those that rule. Part of the models and other materials to be integrated are typically produced during the project at hand, thus the actual compilation of the integrated model is usually possible not until the end tail of the project. The salient processes of the system are then learned by studying the model and sometimes they are found to be those that have actually been playing the minor roles in the project. For example in the case of application presented in paper III, plenty of effort was put on the modelling of ship collisions and oil recovery, whereas based on the results, the formation of the oil leak was actually the key factor in the system. Also in the model of paper II, the main focus was in the oil combating process and practices, whereas the results showed that additional knowledge concerning the weather and drifting of the oil would be more relevant when optimizing the disposition of the combating vessels.

Both Ascough II et al. (2008) and Skinner et al. (2014) denote that complexity of an environmental assessment model is not a measure of its goodness. Even a detailed approach may lack the understanding about those dynamical mechanisms important to environmental decision-making. In stead, a simpler version, where only the salient processes are considered, may do the job. On the other hand, as Pollino et al. (2007a) state, if trying to look for only the simple explanation for a complex system, there is a high risk that important causal factors will be left outside the analysis. Those models may lead to poor management decisions, followed by costly rehabilitation work. This favours the approach of starting with more complexity by utilizing all the available information that is relevant to the research question, and then striving towards “informed simplification” based on the results. This principle is applied in paper III, where a simplified version of the complex oil recovery efficiency model (paper II) is utilized with the accuracy relevant to the analysis in question. However, this is not always possible as building detailed models for each element of a wide topic may take too much time from the project’s viewpoint. To me, learning and developing methods and frameworks for the search of optimal complexity, is one of the future challenges with which to wrestle. Tiered approaches segregate the analysis in tiers where the level of model complexity or resolution is gradually increased where necessary (e.g. Smith et al., 2007 (b); Hobday et al., 2011; Tighe et al., 2013). In the case of a BN, this could mean adding the structural complexity (more nodes and/or causal links, the less parsimonious discretisation of the variables), moving from a qualitative approach towards more quantitative one or from light prior assumptions towards more elaborately defined degrees of belief. Interesting examples of the conceptual modelling and BNs using light priors have been published by Biederman and Taroni (2006), Hui et al. (2008) and Mäntyniemi et al. (2013).

Usually the type, form and accuracy of the knowledge included in the integrated model are heterogeneous (Skinner, 2014) and the integration occurs on multiple levels (EPA, 2008). The restricted resources often force the system modelers to use existing models and other components that are not originally designed to communicate with each other. Thus it is important to verify the conceptual compatibility of the elements to be linked (McLaughlin, 2012; Laniak et al., 2013). In the research consortium, the system modeler should be a kind of co-ordinator, who is acquainted with the work of statisticians, domain modelers, field workers and other specialists providing material for the application (Kragt et al., 2013).

When it comes to the linking of two existing BNs, it is of utmost importance to go through them carefully, node by node and link by link, to understand their logic and the questions they are capable of answering. Also, if planning the extension of the BN developed by some other person, the existing model should be first worked out thoroughly by the continuator, optimally with the original developer. It may be that the existing BNs are not recoverable as such, but the problem may be solved by removing, adding or turning around some arcs and updating only the related probabilities. It may also be that not the whole model, but some particular parts of it can be integrated into the new application. When it comes to building of large BN complexes, Chen and Pollino (2012) highlight the importance of careful documentation of all the assumptions, including uncertainties, descriptions and reasoning for each node and link, as well as the sources of data and other information used. I suggest taking the use of the node properties windows, if provided by the BN software used, to make notes concerning the assumptions made and materials used for populating probability tables. This will be helpful for the further use of the model, as the notes always follow it.

4. BN solutions for typical ERA arrangements

In this chapter, solutions on how the typical arrangements in the environmental decision analysis can be constructed with the Bayesian networks are presented. Simplified graphic presentations are provided and explained. The presentations show only the most relevant structural elements to illustrate the idea. The vague ”System” – presented here as a black box –like submodel - can represent any system with the variables that are relevant to the analysis at hand. In practise, this system would include certain input nodes, which the decisions (denoted with D) somehow affect. The inference in the system would aim for producing information about the likely status of certain output variables of interest. The system is thought to consist of probabilistic random nodes.

From the system’s output variables, the links are drawn to the diamond-shaped utility nodes denoted in the following figures by U/L. The letter L is for ”loss”, to highlight that the node can have also negative values and that in some cases the maximal utility means the minimal loss. In an ID, the utility nodes define those criteria against which the decisions are evaluated and ranked. The utility node is needed also when the informativeness (from the perspective of decision making) of the system's variables is evaluated by using the VOI analysis. From the perspective of policy optimization or VOI analysis, the actual values addressed for the alternative outputs in the utility node are not always important. The most relevant information often is their mutual relations, i.e. how much more we weight some output in relation to another. The monetary valuation approach can make the exemption in case that we want to evaluate the cost-efficiency of some new monitoring program (via the VOI analysis) or management investments.

4.1. Multiple decisions and / or multiple objectives

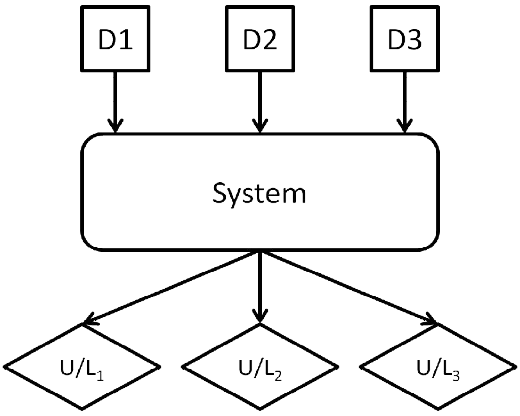

Figure 4. Basic ID arrangement with multiple decisions and multiple criteria.

Figure 4 illustrates a typical decision problem with multiple decisions to be made in parallel, and/or with multiple criteria for the decision ranking and evaluation.

The arrangement with several decisions to be made in parallel is presented in paper II (also Figure 3). There, ten oil combating vessels should be dispositioned optimally in four alternative harbours. Thus, each ship is given an identical decision node having the harbours as its alternative states. A policy updating algorithm, if provided by the BN software, is useful in solving a decision problem of that complex. In Hugin software, the algorithm is called Single Policy Updating (SPU) algorithm (Lauritzen and Nilsson, 2001). SPU updates the policies one by one to the states producing the maximal expected utility, taking into account the prevailing uncertainty in all the random nodes as well as the possibly locked variables. In case that the order in which the decisions are made is relevant, it can be pointed by adding arcs between the decisions correspondingly.

In paper I, three decision nodes represent the country-specific nutrient abatement policies, every nation being given individual amount of alternatives. The objective is to study their effects as separate as well as their synergies, taking into account the uncertain precipitation. In paper III in turn, two alternative accident preventative actions are given the decision nodes of their own, including the alternative states of implementing or not implementing them. These two risk control options are then compared and their synergy is evaluated. When it comes to the decision variables, it is noteworthy that in papers I and III they are used not only for the actual decisions or policies to be analysed, but also for making certain settings in the model. This solution is helpful when studying the results, as no separate model files are needed, e.g. for distinct areas or perspectives on the valuation. However, the model user has to be careful with them, not to draw incorrect conclusions.

In a multi-criteria decision problem, the optimal decision is based on the several parallel criteria or objectives. The model of paper I is actually a multi-criteria problem – even on two levels. First of all, the ecological status of a single area is defined based on the statuses of five indicator variables. In the end, the total utility is defined based on the predicted status of all four coastal areas covered by the study. However, in this case the indicators are first drawn together into random variables of the total areal ecosystem statuses, which are further on collected and compiled into a single utility node. Thus, every multi-criteria ID does not need to contain multiple utility nodes. In the case of paper III, in turn, multiple utility nodes are included in the ID, but the formulated decision problem is still not actual multi-criteria issue. Instead, the utility nodes are handled as alternative decision-making objectives.

In the case of using parallel utility nodes, they should adopt the same unit. Otherwise their mutual proportioning does not make sense. For example, if all the utility nodes of the model in paper III were used side by side, the model would proportion annual numbers of tanker collisions or oil leaks to the annual oil tonnages ending up to the sea. If this kind of synthesis of the results was our objective, different states of the target variables should be given points on a common scale to tell what we think about their mutual weighting.

4.2. Cost-efficiency as a criterium

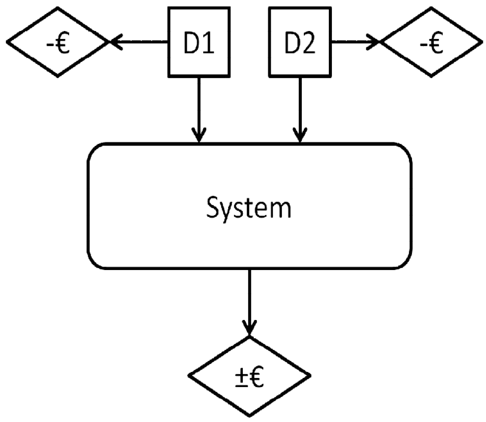

Figure 5. An ID arrangement applying cost-efficiency as the decision-making criterium.

Cost-efficiency is commonly used criterium when choosing among the alternative decisions, probably because it is easy to conceive. The implementation and maintenance costs of the management measures are evaluated against the upcoming profits or savings gained with the implementation if compared with the development without taking the measure. In the case of eutrophication, turning the state of the ecosystem better than today might produce some profits e.g. via healthier fish stocks. If the state did not turn to better, but the process of eutrophication would be stopped, some spares might be gained in anyway, if comparing with the situation where the negative development continued. The basic arrangement of a BN for cost-efficiency analysis is presented in Figure 5.

4.3. Multiple views on the objectives

In many environmental decision-making cases, a variety of stakeholder views should be taken into account (Dietz, 2003). Figure 6 shows one possible ID structure, whereby the weighting of the objectives, by multiple actors can be taken into account. A separate node is added for the stakeholders, including a state for each of them. As the number of states in a discrete random variable is restricted, in the case of large amount of people, they have to be grouped (e.g. “fishermen”, “waterfront owners” and “oil companies”).

For each decision making criterium, two random nodes are added. The first one, denoted by W in Figure 6, is for weighting the criterium in relation to the other criteria. A suitable scoring for this purpose has to be agreed first. Thus, all the W variables have identical amount of states, for example point values from zero to five. If necessary, a preference function node (denoted by PF in the Figure 6) can be associated with each criterion too. The PF defines how much the actor prefers each state of the (criterium-forming) target variable, compared with the previous state (Hyde and Maier, 2006). One possibility is to provide some fixed PFs defining that the increase will follow the

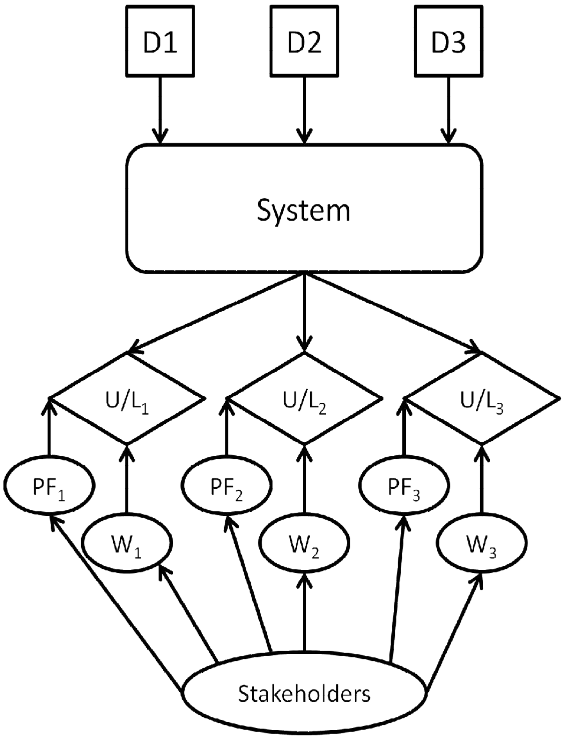

Figure 6. An ID arrangement for including the varying values and weights of the stakeholders.

same logic on each step, such as "equal", "linear" and "exponential" value growth. This enables the use of mathematical equation for the utility function.

A brilliant feature in the presented structure is that the variability in the views of the stakeholder groups can be included in the CPDs of W and PF nodes. As a consequence, the actor-specific views are preserved and the problem can be easily analysed and compared also from the perspectives of different stakeholder groups. This might provide a valuable demonstration tool for stakeholder meetings. With the help of the VOI analysis, it is also possible to study and demonstrate how much it actually matters, whose objectives are taken into account when it comes to the decision making and choosing the best action or policy. If necessary, the weighting of the actors can also be done by modifying the probability table of the variable "Stakeholders" accordingly.

4.4. Multiple opinions on how the system works

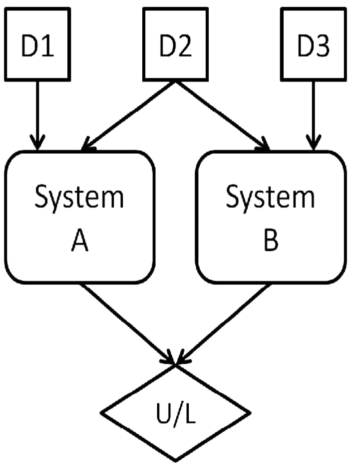

Figure 7. An ID arrangement for two alternative models about the system.

By involving stakeholders in the management process already in the analysis phase, their willingness to commit to the decisions made can be increased (Haapasaari and Karjalainen, 2010; Levontin et al., 2011). This may affect the success of the policy implementation. In some cases the stakeholders have differing views on how the whole system actually works (e.g. Pollino et al, 2007b; Mäntyniemi et al, 2013). This may affect their thinking on how it should be managed. In that case better alternative than to force the stakeholders to create a consensus model, which no one fully accepts, is to construct the models of their own and handle them as alternative realities. These stakeholder-specific models can be included to the larger ID as submodels (Figure 7) and the integrated model then used for analyzing and demonstrating the situation. In Figure 7 both the models have common objectives, but it might be that also the objectives are varying and several utility nodes were needed.

In paper III, uncertainty arising from multiple alternative models predicting the emergence of hull breach in the case of a tanker collision, is considered. In that case it was not reasonable to include own submodels for each, but the model-specific estimates were included with the same principle as the stakeholder views in Figure 6. Also if multiple experts are providing their degrees of belief about the same issue, their views can be involved by applying the same logic (this is applied for the expert elicited future scenarios in paper III), so that the pooling of the opinions is avoided and the gathered information preserved to the extent possible.

5. Locating the presented BN applications into a DPSIR framework

This thesis is based on five scientific papers, four of which (I-IV) are presenting BN applications for ERA. The applications take different perspectives on environmental risks posed by human activities and cover a variety of both societal and ecosystem elements. In this chapter, the contributions of the applications are presented in the broader societal context. The DPSIR (Driving forces – Pressures – States – Impacts – Responses) framework is used to contextualize the work done. This framework is a widely used problem structuring method in the field of environmental management analysis. It strives for capturing and representing the causes and consequences of environmental change as well as the human responses in a systemic way (Gregory et al., 2013). The approach has been utilised in divergent manners in a variety of environmental scientific papers, e.g. in the fields of Water Framework Directive (Borja et al., 2006), the coastal management (Bell, 2012), sustainability studies (Bidone and Lacerda, 2004; Ness et al., 2010), climate change (Holman et al., 2005) and loss of biodiversity (Maxim et al., 2009; Gregory et al., 2013). The elements and links of the DPSIR framework are presented in Figure 8 of chapter 5.1.

Among the environmental management scientists, interest in the systemic problem structuring methods, such as the DPSIR, is claimed to be relatively new phenomenon (Paucar-Caceres and Espinosa, 2011; Gregory et al., 2013). They are still seen to be potential tools for the environmental management scientists tackling with the complexity and multidisciplinarity of the topic (Paucar-Caceres and Espinosa, 2011). However, DPSIR is still criticised to lack the participatory elements, which are important in the real life environmental management, where the stakeholder involvement and the public discussion should be part of the process. The approach is blamed to represent only the viewpoint of researchers and being defective when it comes comes to the inclusion of multiple perspectives on objectives or even the system's functioning principle (Svarstad et al., 2008; Tscherning et al., 2012). To me it seems that the actual problem is the framework being in some cases understood quite narrowly. By taking a broader view and complementing with a suitable analytic methodology, the DPSIR approach could be applied in even wider variety of environmental cases for structuring the work and helping in the systematic thinking of the issue. This kind of application could also have potential to serve as a tool for demonstrating the system's working and thus supporting the discussions with the stakeholders and in public (Bell, 2012).

Despite their shared causal nature and suitability for problem structuring, BNs have not been applied for analysing the DPSIR chain in practice although the idea has been touched on (Barton et al., 2008; Niemeijer and de Groot, 2008). Niemeijer and de Groot (2008) suggest that instead of the oversimplified presentation (see Figure 8), each element of the DPSIR could be seen as a subsystem of its own, consisting of several variables having interlinkages between them. They suggest moving from the causal chains towards the causal network analysis and mention BNs as one possible approach. I agree with their idea and try to concretize it here by planting in the framework the BN-ERA applications presented in papers I-IV. It should be noted that every ERA does not need to cover the full DPSIR. Suitable pieces of information or models can be linked to form the full analysis thanks to the integrative approach and methods. In any case it is always useful to locate one's study into the broader societal framework, part of which the DPSIR represents, to better conceive the added value that the work produces. This procedure may also help in the search of suitable models and materials to be integrated, as well as in the detection of the missing pieces and next steps to be taken in the research.

5.1. Elements and links of the DPSIR

The definitions of the DPSIR elements tend to vary depending on the context and perspective. Some examples from the literature as well as the definitions used in this text are provided below:

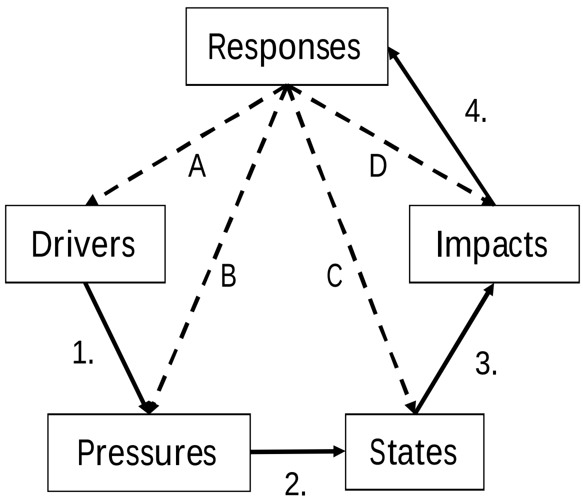

Figure 8. The full DPSIR framework. Elements and links are explained in the text.

Drivers are defined in the science articles e.g. as ”the forces that act on the environment” (Niemeijer and de Groot, 2008) as well as ”the forces behind the social and economic development” (Gregory et al., 13). In this thesis, Drivers are seen generally as the forces, controlled by the human needs, that drive the change in the environment. Drivers define the level of Pressures falling on the environment. Different economic and political trends are typical drivers.

Pressures can be outlined e.g. as ”the ways that the Drivers are expressed and the ecosystem and its components perturbed” (Borja et al., 2006), or simply as ”the causes of the problems” (Gregory et al., 2013). In this thesis, Pressures mean the factors that are causing or have potential to cause changes in the state of the environment. Nutrient loading to the watersheds is one example of the pressure factors.

States may describe e.g. ”the change in the background status of the environment” (Gregory et al., 2013) or ”the changes that take place in the environment” (Niemeijer and de Groot, 2008). Here, term States (in the DPSIR context) is used for the overall changes in status of the environment. When it comes to the previous example of nutrient loading, the increase in the nutrient concentrations of the water and all the consequent changes in the ecosystem (i.e. the process of eutrophication) would be grouped under this element.

Impacts can be defined as ”the impacts on society” (Gregory et al., 2013), ”the societal reaction to the changes in the environment” (Niemeijer and de Groot, 2008), or similar. This element is addressed with the greatest risk to be misunderstood (Gregory et al., 2013). Noteworthy is, that the impact on environment was included already in the previous element (States), thus in this context the element Impacts refers to the societal impact caused by the environmental changes. In other words, Impacts is the element where the objectives (i.e. values and weighting) of the society speak. In practise, the level of impact is defined by using some classifications or boundary values that should be those commonly used and accepted by the society (although often suggested by the scientists). In the case of eutrophication, divergent indicators are commonly used to evaluate and classify the state of the system. Objectives of the stakeholders could also be used to define the Impacts.

Responses, as adopted also in this work, are the various management measures that can be directed at any other element of the DPSIR system (Borja et al., 2006). The willpower of decision makers, influenced by the information from scientific analyses as well as the public debate, remarkably affects the selection of responses and response levels (Burgman, 2005; McLaughlin, 2012). To define the need for the response, a clear target level or acceptable level for the impact indicators should be defined.

In the present work, the links (1-4 in Figure 8) between the elements define:

1. The level on which the certain need creates pressure
2. The degree to which the system is affected by the certain level of pressure
3. The harmfulness of the change (i.e. how the society valuates it)
4. The need for management, given the chosen objectives

The Response-links A-D in Figure 8 describe the different routes to manipulate the system. For example, a case where the demand for some product (e.g. fertilisers or oil) would decrease as a result of certain political alignments, is represented by the link A. Link B, in turn depicts controlling the degree of pressure that is created by the certain level of need. Intensification of the municipal waste-water purification or the measures promoting the safety of maritime traffic are examples of that kind of management. All in all, links A and B are about managing the causes of the (potential) environmental change, whereas the actions striving to control the consequences in the ecosystem, is represented by the link C. In risk assessment terms, link C would mean managing the harm (consequences) that certain level of pressure (event) poses to the system. As a result of assessment, we can also come to a conclusion that our objectives (or how they are evaluated and defined), would need revision. This is the case described by the link D.

The most remarkable structural differences in the published DPSIR presentations are related to the amount of Response-links included. In some studies, either link A or D and sometimes them both are left out (Niemeijer and de Groot, 2008; Svarstad et al, 2008; Ness et al., 2010; Bell, 2012; Gregory et al. 2013), but also articles where all the links A-D are included exist (Holman et al., 2005; Maxim et al., 2009).

5.2. Case studies in the DPSIR framework

In this chapter, the case studies presented in papers I-IV are located into the DPSIR framework as simplified causal networks. The idea and the manner of representation are suggested by Niemeijer and de Groot (2008).

Eutrophication and the risk of not reaching the target state

In the first article (paper I), the full DPSIR cycle is covered (Figure 9). The paper studies the nutrient loads to the Gulf of Finland from three coastal countries. The resulting state of the ecosystem is analysed in the Finnish coastal area from the perspective of the ecological status classification (ESC) of the European Water Framework Directive (WFD). The risk that the objectives of the WFD (at least ”Good” ecological status) are not fulfilled by the target year 2015, is in focus. The presented BN model integrates the results of existing nutrient load and ecosystem response simulations with the evaluation principles and objectives defined by the WFD guidelines. As illustrated in Figure 9, the background assumptions behind the nutrient loading, concerning the future changes in the operational environment of different sectors, can be seen to represent the Drivers in this case. These changes mean, for example, the assumed structural change of the industry and agriculture. The Drivers of nutrient loading are not specified in paper I, but they are taken into account in the loading scenarios that follow the divergent nutrient abatement measures. The detailed descriptions for Drivers of the model are provided in the works of Rekolainen et al. (2006) and Pitkänen and Tallberg (2007), from which the nutrient abatement scenarios originate.

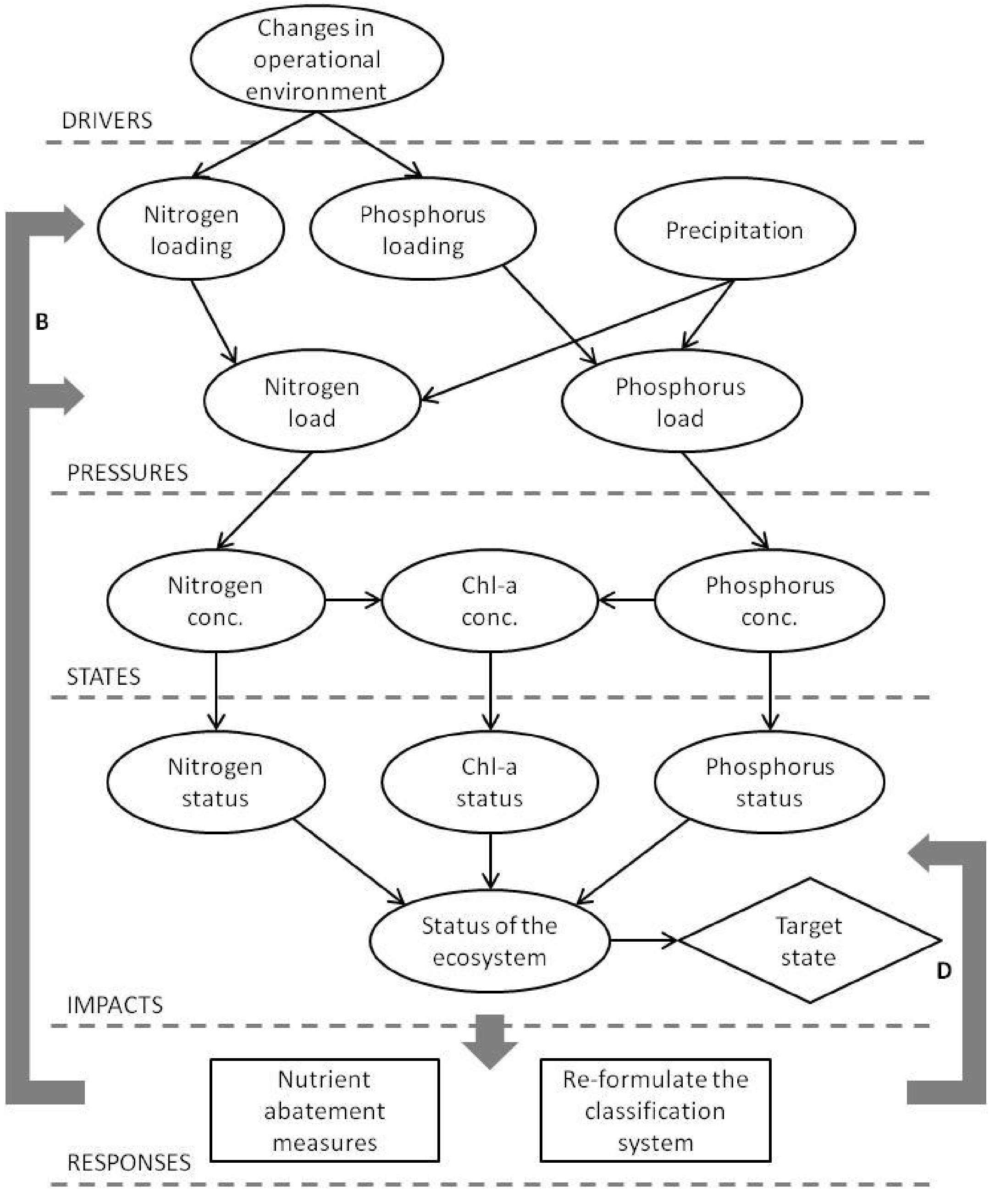

Figure 9. A simplified version of the causal network analysis conducted in paper I divided up into the elements of DPSIR framework.

Both the nutrient loading in the catchment and the resulting nutrient loads to the sea represent the element Pressure. As an external pressure factor, the uncertain development of precipitation is added. The precipitation affects the washing of the nutrients from the land areas, thus influencing the resulting nutrient load to the sea, given the volume of anthropogenic loading in the catchment area.

The element States is covered by the measurement units on which the status classification of the indicators is based, for example the concentrations of the total nutrients and chlorophyll-a in the surface water. These nodes are not included in the graphical presentation of the model but exist on the background. Impact is defined based on the ecosystem status evaluation principles provided in the Finnish WFD guidelines (Vuori et al. 2009). Thus, ”status” in this case means the artificial status classes created to reflect human objectives, which is the reason why they are located into this element. The final objective is to gain at least good general state (based on the statuses of the indicators) of the ecosystem. In the model, this is used as the criteria against which the analysed nutrient abatement measures are evaluated (denoted by a diamond shape). Concerning the management links shown in Figure 8, the arrows B and D are studied. Link B is represented by the management actions that affect either the loading from the land areas (e.g. new restrictions for the use of fertilizers in agriculture and forestry) or the final nutrient load ending up to the sea (e.g. changes in the forestry draining practices or the more efficient purification of the municipal waste waters). Related to the link D, paper I studies the alternative ways to define whether the objectives of the WFD are fulfilled or not. The differences arise from the differing techniques of defining the general status of the area based on the statuses of the indicators. The meaningfulness of the current classification system is consequently discussed.

Oil transport and the risks of spills

Papers II-IV handle the evaluation and management of the environmental risks caused by the oil transport at the densely trafficked Gulf of Finland. In paper II, the open sea oil recovery efficiency of the Finnish oil combating fleet is maximised by optimising the disposition of the vessels. That model is integrated into the application of paper III, analysing the effects of two accident preventative measures. Paper III also studies, how well different parts of the model can be managed by those two actions, when taking into account the uncertainty which cumulates along the additional elements in the system. The analysis in paper III ends up to the predicted amounts of oil drifting to the coast annually. Paper IV takes a step towards the spatiality of the risk and the ecological consequences of an oil accident, by defining the loss through the oil drifting and the exposure of the threatened species. In that paper, software that integrates a BN, oil drift simulations and a database for the observed occurrences of threatened species, is presented. A direct decision analysis is not a feature of the software, but its interactive nature enables the user to manipulate the model and in this way to analyse, how the changes in certain parts of the system affect the spatial distribution of the risk.

The entity covered in papers II-IV is planted in the DPSIR framework in Figure 10. None of the papers as such cover the full DPSIR arrangement. Integration of the separate analyses into the same chart was not an easy task, because they take slightly different perspectives on the issue. In papers II and IV a single oil leak and its consequences are considered, whereas paper III operates on the annual level by analysing the number of collisions and leakages as well as the following volumes of oil in the ecosystem. On the other hand, this type of issues need to be considered when creating integrative models, the issue being discussed in Chapter 3.

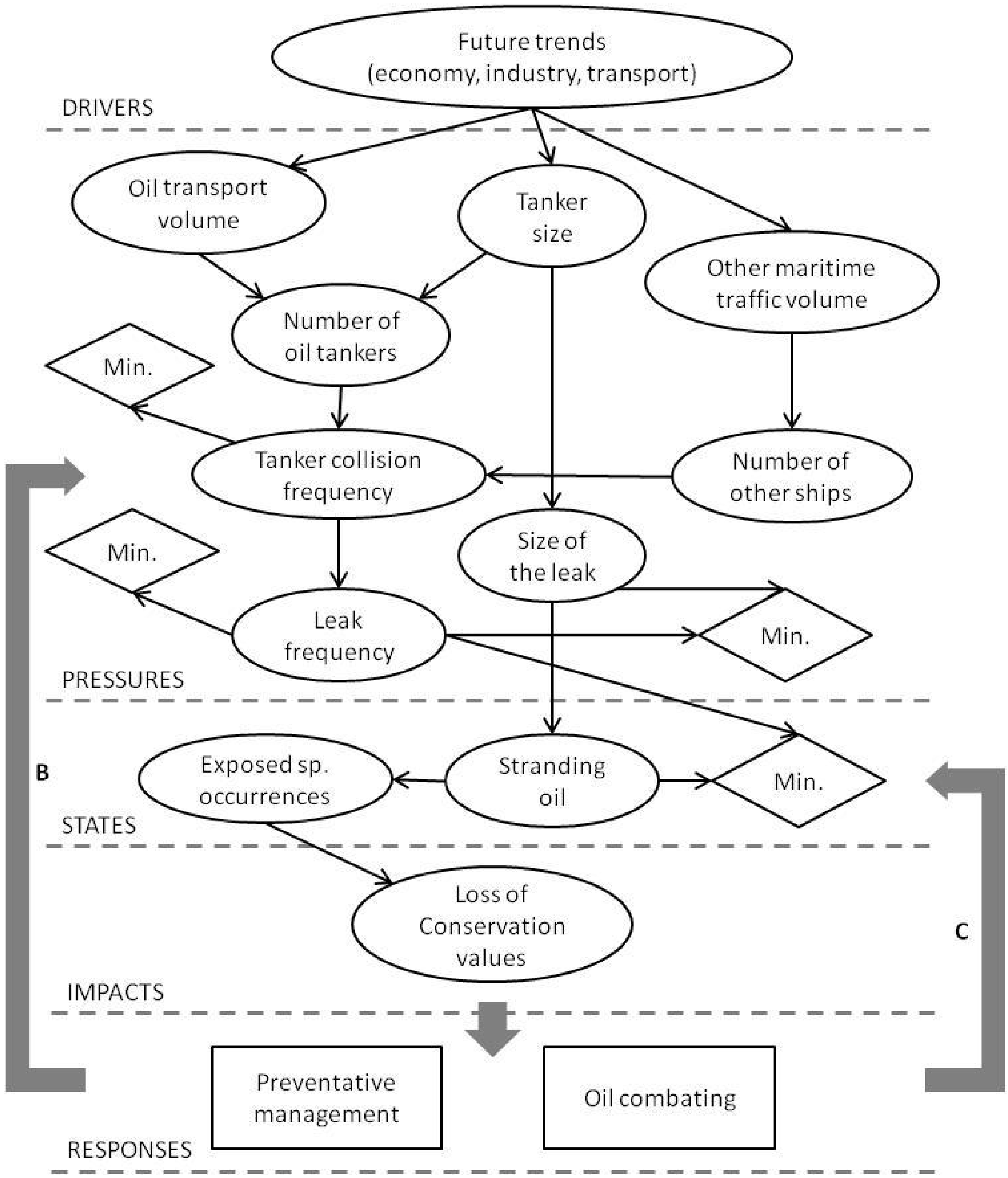

Figure 10. A simplified version of the causal network analysis conducted concerning the oil transport driven risks, divided up into the elements of DPSIR framework. The research questions of papers II-IV are integrated into the same chart.

Drivers of the entity in Figure 10, are the assumptions on the economic, industrial and transport trends, affecting behind the future maritime traffic and oil transport scenarios used as a starting point for the analyses (papers III and IV). Element States includes the corresponding traffic parameters and the following accident and oil spill frequencies (papers II-IV). States also cover the level of pollution, i.e. the amount of oil in the ecosystem (papers II-IV) and, in the case of paper IV, the exposed occurrences of the threatened species, for which the possibility to lose whole populations or remarkable parts of them is higher than for common species. The open sea oil recovery model (paper II) represents the management link C, affecting the final amount of oil that will stay in the ecosystem after a spill. The risk control options that strive for decreasing the collision probabilities (paper III) correspond the link B. In risk terminology, the preventative control options are aimed for managing the probability of the event (oil spill), whereas oil combating is about managing the consequences by decreasing the amount of harm if the accident comes true.

For the entity formed by the papers II-IV, the only aspect for which some valuation guidelines are provided by the society, are the threatened species located in the element Impacts. In the software of paper IV, the mutual weighting of the species is based on the conservation value index, originally published by Ihaksi et al. (2011), covering multiple valuation criteria, e.g. the IUCN status classification and legislative aspects.

Not any official indicator or other measure for the acceptable level of risk posed by the oil transport have been defined for the GoF. One reason probably is that discontinuation of the transportations in the international sea area is not an option in anyway. Thus, in the decision analysis of paper III, the minimum achievable level of risk is used as the objective. As stated in paper III, risk is a perspective dependent concept and within a causal model several event-consequence pairs to be analysed occur. A variable representing the consequence of the previous node may be causing another. Thus, in paper III, the risk is studied from four different aspects (each of them to be minimized), denoted by the diamonds in Figure 10: the frequency of tanker collisions or oil leakages, as well as the annual volumes of oil drifting to the coast with and without the oil combating.

Noteworthy is that because the decision analysis presented in paper III doesn't cover the whole DPSIR, the criteria against which the decisions are evaluated (the diamonds) are in this case not located under the element Impacts (Figure 10). Despite that, the analysis can be seen as *environmental* risk assessment as the decisions aim for decreasing the potential environmental pressure. The results of paper III exemplified that the uncertainty related to the efficiency of the preventative risk control measures increase the further in the inference chain the decision criteria was located. Thus, it will be interesting to see the results, once the approaches of papers III and IV will be integrated so that the ecosystem level losses can be used as the decision-ranking criteria.

Also in the case of oil transport driven risks, an external pressure factor outside the human control is involved in the analyses (papers II-IV), namely the seasonal changes in weather patterns. They affect the accident frequencies (paper III), the success of oil combating (papers II-IV) as well as the oil drifting (paper IV). For simplicity, this seasonal element is left out from Figure 10.

6. System's analytic insights into eutrophication and oil spill related risks

In the case studies included in this thesis (papers I-IV), two very different types of environmental risks are considered. Paper I studies the risk that the objectives set by the society, regarding the ecological status of the Gulf of Finland, will not be met by the target year (2015) given. The unwanted event is that the fixed tipping point between ”moderate” and ”good” state will not be surpassed. The utility function of that case study is as simple as the objective: if the goal is not reached, the utility is set to zero, otherwise being one. The decision analysis aims to study, how much the risk could be decreased by implementing certain nutrient abatement policies in the coastal states surrounding the gulf.

In paper III, the oil transport driven risk of an oil accident at the Gulf of Finland is analysed. In this case, the oil tanker collision leading to an oil leak is considered as the unwanted event. The time window for which the probability of such accident is estimated, is one year. The final level of harm is defined by the amount of oil that will leak to the sea and cannot be recovered by the oil combating vessels. The decision analysis aims to study, how effectively the risk could be decreased dy two accident preventative measures. Paper IV takes a different view. The software presented in that article evaluates the spatial ecosystem risk posed by a single random oil accident. The unwanted event is that a map grid cell including the known occurrences of threatened species will be exposed to oil. The amount of harm is defined by the number and ”value” of occurrences within the exposed cells. The value of an occurrence results from a conservation value index (developed by Ihaksi et al., 2011), covering both societal and biological criteria, weighted by a group of experts.

It is evident that the risk related to both nutrient loading and the oil accidents could be evaluated from numerous perspectives different than those presented. Anyhow, the point of this chapter is to bring out the system analytic insights that I have gained while working with these two environmental risks and highlight the central differences between them.

Eutrophication is an ongoing, relatively well-studied process. There are still plenty of uncertainties related to the issue. For example: a) what is the exact phase of the process and how it will develop in the future, b) what is the true state of the system and are there some specific tipping points where its status would remarkably change, c) what is the minimum level to which we should strive for and d) how much we can affect the situation and how long it will take to the system to respond. If compared with the oil spill risk, eutrophication is different in the sense that by implementing management actions, we can very likely make the state of the ecosystem better (sooner or later). Recovery is expected to produce more ecosystem services and can thus be seen leading to economic profit, which makes it easier to justify the investments of the society. Still, there is a risk that despite the investments, the state of the system continues going to a worse state. This can be e.g. because of the internal processes of the ecosystem (internal loading) or because new sources of external loading or other stressors have arisen. It may be hard to justify new conservation investments if it seems that the ecosystem is not responding.

The nutrient abatement measures cause acute losses for certain parties, e.g. farmers and industry. The future gains in turn will be directed mostly to other parties, for example the fishermen and recreational users. On the other hand, the losses and gains of the enterprise sector will, before long, fall on the consumers anyway. Here is a place for the societal risk communication: what is the minimum acceptable level for the ecosystem status and how much uncertainty people are ready to accept concerning it? Further on, how much they are willing to invest in gaining their objectives, and who should pay what. These views should be gathered and used to inform the future decision analyses.

Compared with the eutrophication, the risk of an oil accident is more abstract. The preventative management actions are implemented to decrease the probability of a potential event potentially leading to major losses. By implementing additional regulations, we may succeed in preventing these huge losses, but the spill may still occur some day in anyway. If we don't invest in maritime safety, there will be higher probability for an accident but it is still possible to go the next ten years without any. When the action is implemented, it is difficult to assess how effective it has actually been. To some extent, this would be possible for example by studying the near miss accident reports or through interviewing the seafarers. Anyhow, both defining the ”state” of the system and monitoring the efficiency of the actions is much more difficult in this case than in the case of eutrophication. As the system is difficult to observe, evaluating it rests more on the theoretical analysis, i.e. modelling.

As long as the oil is transported, the risk for an oil accident exists. Again, more societal debate and studies on people's values and risk attitudes are needed to figure out, how high risk people are willing to accept, versus how much they are ready to pay for decreasing it. Depending on the controlling measures taken, the costs may fall on the oil companies, shipowners or the coastal countries. Probaby for all of them but in different ratios and through different mechanisms. In the end, all the additional costs will very likely show in the price of the oil. As the utility of the investing in maritime safety is even more invisible to common people than in the case of eutrophication, it may be more difficult to get societal support for it. After one large oil spill the situation might change totally, but the prize would consist of several immeasurable losses.

As the risk- and situation awareness are also remarkable factors affecting the people's risk attitudes, media and research community have a key role in informing the citizens about the environmental risks. It is only minor part of the aquatic ecosystem that most of the people ever see. Concerning the eutrophication, the most well-known ecosystem's status indicators are probably the blooms of toxic blue-green algae, or the water clarity. Fortunately, the Gulf of Finland has so far managed to avoid the large scale oil accident and people have not experienced the consequences. For these reasons it is important to produce material for common public, informing them about the risks, the current state of the environment and its development (also the positive), telling what kind of values are at stake.

A common feature for both of the environmental risks handled in this thesis is that they are strongly international issues. Major parts of the seas are internationally administered. In addition, the nutrients as well as the oil tend to drift in the sea regardless of the state frontiers. I see that visual integrative tools, such as BN based ERA models, have potential to support the consensus building when common laws and regulations and policies are negotiated.

7. Discussion

This thesis considers the Bayesian networks (BN) as tools for creating environmental risk assessment (ERA) models. To me, par excellence, BN is a tool for synthesizing knowledge, logic and rules. It represents artificial intelligence, providing aid for thinking about complex systems that are too demanding to be analysed by human brains alone. Typical ERA problem is complex and multidisciplinary by nature. The model for aiding the risk assessment process should provide a holistic and conceivable view on the system in focus and in this way help understanding its dynamics and possible response to the analysed management measures. I have demonstrated that Bayesian networks as method have plenty of properties that are useful for ERA and they can be used in solving analytically problems typical for that field.

I have used the DPSIR (Driving forces – Pressures – States – Impacts – Responses) framework to conceptualise and summarise the work done in papers I-IV. The graphic BN is helpful in conceptual modelling, enabling the framing of the research problem at hand and thinking about it systematically (Chen and Pollino, 2012). The added value of a DPSIR framework in turn, is that it can help in putting the elements of analysis into a societal context. I see that the combination of BNs and DPSIR forms a holistic framework for structuring the management problems as well as the research needed to analyse them. In addition, the synthesis of these two approaches could provide a good basis for planning the integrative ERA models and projects. On the other hand, when planting the work done into the DPSIR frames, I found that the boundaries between the DPSIR elements are in some cases vague. The varying definitions in the literature support this observation. Thus, the itemisation of the model variables and thinking through their role in the wider societal scale was useful but not self-evident. It is also noteworthy that all the BNs or ERA arrangements do not form the full DPSIR, but both can cover only some parts of it.

The DPSIR analyses seem not to extensively handle the uncertainty related to the causal links between the elements. I think that bringing in the probabilistic way of thinking by adopting BNs as tools for the analysis, would produce remarkable added value. The DPSIR framework is clearly cyclic by nature, which is mentioned problematic when it comes to its presentation with the BNs (Barton et al., 2008), because of their acyclicity. This problem can be overcome by the means of time-slicing, i.e. replicating the system for each time-step (e.g. Weber, 2006; Johnson and Mengersen 2012). By drawing a link from the previous time-step to the next, the system apparently updates itself.

Integrated assessment models are typically problem-focused and needs-driven (Jakeman and Letcher, 2003), which may sometimes collide with the scientific ambitions of the research organizations, especially the universities. On my opinion it is still important that the work is based on the scientific thinking and criteria, to be of high quality. As Jakeman and Letcher (2003) state, ”the science (of integrated modelling) is not always new but the work is intellectually challenging”. Sakari Kuikka, one of my two supervisors in turn often highlights that one central legitimacy criterium for the scientific work is that it has to be societally useful. According to McNie (2007), the boundary that demarcates science and society, forms a challenge when striving for producing information that is usable for the decision makers. On the other hand, it protects science from politicisation and facilitates the development of credible and legitimate information. To be able to produce scientific information that is truly useful for the society, requires science community to develop in managing the boundary without loosing that credibility and legitimacy.

Publishing a complex integrative metamodel is an art of a kind. First of all, explaining the logic of such entity and justifying all the assumptions made is a long story as such. If the background models and other studies are not published, they should be presented in the same breath. In addition, there are plenty of relevant results to be presented, the actual quantitative measures for the analysed issue being only one aspect (McNie, 2007). The more the domain experts publish their own submodels and other materials in distinct papers (preferably in the early phase of the project), the easier it is to write about the metamodel once it is finalized. All the elements of the model that are interesting as such are worth of articles of their own. This way the description of the metamodel can be remarkably shortened as the published parts can be referred to and described only in short. The development of a BN is also a kind of never ending process (Chen and Pollino, 2012). When the modeller continues to study the topic and working with the domain experts, his understanding about the system updates all the time. After a half year of more work, he might be willing to update the model. Thus it can be problematic to decide, when to publish. It just has to be accepted that the present version represents the current state of knowledge and understanding and for that reason is worth publishing.

To achieve the full societal utility, the developed BN-ERA models should be used to aid real life decision making. One interesting aspect for the future research would be to study the prerequisites for the tools of this kind to become to the true practical use of the managers. The importance of transparency and uncertainty involvement in the assessment models has been emphasized in divergent forums for years already. Still, the majority of the models in authoritative use tend to be deterministic input-output applications. Thus it would be of utmost importance to study, how complex entities the potential end users would really like to analyse and how they actually conceive the probabilistic information. To avoid the misinterpretation of the results, the entity (exact meaning of the variables, the logic of inference, assumptions made and the restrictions of the model, as well as the data used) should be thoroughly understood by the user. On the other hand it could be questioned if they are understood when it comes to the current black box tools either.

The active involvement of the end users into the process of developing the model have been emphasised in the literature (e.g. EPA, 2008; Laniak et al., 2013). This ensures that the model will meet their needs in terms of problem framing and the questions to be answered. Also, if the end user does not agree with the data, assumptions, logic or the methods used for the modelling, it is not possible for them to subscribe with the results either. On the other hand, we could arque that the model might become more objective and useful for the wider audience when developed by a team of independent scientists. The decisions evaluated by the applications of this thesis are rather political and collective than individual or organisational (see Dietz, 2003). Thus the models should be able to indicate the collectively best decisions. This will increase the commitment of the stakeholders, decreasing the uncertainty related to the implementation success of the management measures chosen (Haapasaari and Karjalainen, 2010). I tend to think that some kind of golden mean would be a good solution, where both the end users and the stakeholders are heard but the final model still constructed independently by the scientists.

The transparency and flexibility of BNs provide plenty of opportunities for the end user. However, this comes with great responsibility as - in addition to knowing the model - the user should understand at least the basics of the Bayesian inference and probabilistic way of thinking. If this is not the case, there is a high risk of making erroneous interpretations. It is of utmost importance to acknowledge in every state of the model, the settings made, to conceive the question to which the model is answering in that particular state. The user should also understand the inverse logic of the

BNs, i.e. the bottom-up updating mechanism, as this characteristic sometimes generates results that at first sight may seem rather confusing. For the above mentioned reasons, what I see as realistic alternative when it comes to the end use of the BN-ERA applications, are interactive workshops, where the model developers would act as facilitators by conducting the asked runs, interpreting and explaining the results.

I have experienced the system modeler’s role in an integrative modelling process as challenging and multifaceted. The work is highly multidisciplinary as the person needs to understand the key elements of the work behind the data and materials to be used. Kragt et al. (2013) list different roles of the integrative modeller during the process covering the parts of the facilitator, leader, knowledge broker and technical specialist. Thus, the system modeller coordinates the integration process, as well as realizes the final metamodel. Thinking about the future integrative modelling projects, I would like to highlight the importance of allocating working months for a full-time person who is responsible for that work. To my experience it is absurd to assume that the integration would happen only by ”active cooperation” as is unfortunately often stated in the project plan documents.

Goring et al. (2014) have studied the costs and benefits of interdisciplinary collaboration within scientific community. They state that the scientific reward system is inconsistent with the nature of the interdisciplinary research and projects. To me it was easy to recognise many of the issues they highlight. The process of ”growing into interdisciplinarity” do decrease the academic productivity of an early career scientist. It takes time to familiarise with the topics and the work of the domain researchers, such as statisticians, accident modelers and sociologists, as well as to learn to communicate with them. I see this as partly never ending process as well, because it will start over with every new project and consortium. On the other hand, I feel myself privileged as I have had possibility to meet all those interesting people and learn about the domain topics that I never had even dreamed about. It has been interesting and didactic to familiarize with the working methods and culture of that many disciplines. The communication and co-operation with the new domain researchers progress faster every time because the process covers the same basic elements. As the interdisciplinary research teams and projects are becoming more and more popular, I hope that good practical frameworks and other tools for easing their work will be published. Praiseworthy examples are provided by Catney and Lerner (2009), Haapasaari et al. (2012) and Kragt et al. (2013).

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